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Anatomic Anterolateral Ligament Reconstruction of the Knee Leads to Overconstraint at Any Fixation Angle

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Background: Anterior cruciate ligament (ACL) tears are one of the most common injuries among athletes. However, the ability to fully restore rotational stability with ACL reconstruction (ACLR) remains a challenge, as evidenced by the persistence of rotational instability in up to 25% of patients after surgery. Advocacy for reconstruction of the anterolateral ligament (ALL) is rapidly increasing because some biomechanical studies have reported that the ALL is a significant contributor to internal rotational stability of the knee.

Hypothesis/Purpose: The purpose of this study was to assess the effect of ALL reconstruction (ALLR) graft fixation angle on knee joint kinematics in the clinically relevant setting of a concomitant ACLR and to determine the optimal ALLR graft fixation angle. It was hypothesized that all fixation angles would significantly reduce rotational laxity compared with the sectioned ALL state.

Study Design: Controlled laboratory study.

Methods: Ten nonpaired fresh-frozen human cadaveric knees underwent a full kinematic assessment in each of the following states: (1) intact; (2) anatomic single-bundle (SB) ACLR with intact ALL; (3) anatomic SB ACLR with sectioned ALL; (4) anatomic SB ACLR with 7 anatomic ALLR states using graft fixation angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90°; and (5) sectioned ACL and ALL. Internal rotation during a 5-N·m internal rotation torque and anterior translation during an 88-N anterior load were recorded at 15° flexion intervals between 0° and 120°. Axial plane translation and internal rotation during a simulated pivot-shift test (combined 5-N·m internal rotation and 10-N·m valgus torques) were recorded between 0° and 60°. Kinematic changes were measured and compared with the intact state for all reconstructed and sectioned states.

Results: Anatomic ALLR at all graft fixation angles significantly overconstrained internal rotation of the knee joint beyond 30° of flexion and at 45° and 60° during the pivot-shift test. Furthermore, there were no significant knee kinematic differences between any tested graft fixation angles during anterior drawer, pivot-shift, and internal rotation tests.

Conclusion: Anatomic ALLR in conjunction with an ACLR significantly reduced rotatory laxity of the knee beyond 30° of knee flexion. However, ALLR, regardless of fixation angle, resulted in significant overconstraint of the knee.

Clinical Relevance: ALLR at any fixation angle overconstrained native joint kinematics and should be performed with careful consideration. Further investigation into the application and target population for ALLR is strongly recommended.

Keywords: knee ligaments; anterior cruciate ligament; lateral knee ligaments; biomechanics; anterolateral ligament; rotational instability

Anterior cruciate ligament (ACL) tears are one of the most common injuries among athletes.[29] However, the fact that up to 25% of ACL reconstruction (ACLR) patients report residual rotational instability[43] reveals that the ability to fully restore rotational stability with isolated ACL surgeries remains a challenge. Advocacy for reconstruction of the "recently" described anterolateral ligament (ALL)[46] is rapidly increasing because it has been recognized as a potential contributor to symptomatic residual anterolateral rotatory laxity in ACL-deficient patients.[43] Segond[41] first described the ALL as a pearly, fibrous band that was evident in internal rotation. The anatomic and biomechanical properties of the ALL have been described more recently,[24,36,44] and thus, attempts are now focused on restoring its native function with an anatomic reconstruction.[8]

To our knowledge, there is currently no consensus on the optimal graft fixation angle at the time of ALL reconstruction (ALLR). As anatomic reconstructions are

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becoming increasingly popular, many different fixation angles have been suggested in the literature for ALLR procedures and include, among others, full extension (Sonnery-Cottet et al[43]), 30° (Claes et al[8]), 70° (Spencer et al[44]), 75° (Nitri et al[34]), and near 90° (Zens et al[50]). However, the effects of these variations have yet to be biomechanically evaluated.

The purpose of this study was to investigate the biomechanical differences of clinically relevant knee flexion angles for graft fixation during ALLR in the setting of a combined ACLR and to determine the optimal fixation angle for ALLR. It was hypothesized that all graft fixation angles would significantly reduce rotational instability compared with the sectioned ALL state.

METHODS

Specimen Preparation

A total of 10 nonpaired fresh-frozen human cadaveric knees with no prior injury, surgical history, or gross anatomic abnormality (mean age, 55.9 years; range, 46-64 years; all male) were included in this study. All specimens were stored at −20°C and thawed at room temperature for 24 hours before preparation. The femoral and tibial diaphyses were cut 20 cm from the joint line. All soft tissues on the tibia and femur within 10 cm of the joint line were preserved. The remaining soft tissues were removed to expose the tibia, fibula, and femur to be potted in polymethyl methacrylate (Fricke Dental International Inc).

Before the specimen was mounted in the robotic system, a medial parapatellar arthrotomy was performed, and the menisci, cartilage, and cruciate ligaments were examined to evaluate for any pathologic abnormalities. Similarly, in preparation for a later ALLR, a lateral hockey stick–shaped incision was performed, followed by careful dissection to the iliotibial band (ITB). After identification of the relevant structures, sectioning, and surgical procedures, soft tissue and skin incisions were closed before each testing state with No. 2 polyethylene/polyester sutures (FiberWire; Arthrex Inc). Surgical procedures were performed with the knee mounted in an inverted position within the robotic system throughout all testing states to reduce possible testing error introduced from specimen removal, as previously reported (see Appendix Figure A1, available in the online version of this article and at http://ajsm.sagepub.com/supplemental)").[18,19]

Robotic Testing Setup

Knee biomechanics were evaluated with a 6 degree of freedom (DOF) robotic system (KUKA KR 60-3; KUKA Robotics), which has been described and validated previously for knee joint testing.[18,19] The potted tibia and fibula were secured to a universal force/torque sensor (Delta F/T Transducer; ATI Industrial Automation) attached at the end effector of the robotic arm via a custom fixture, and the potted femur was securely mounted to a stationary pedestal (see Appendix Figure A2, available online).

After the specimen was mounted within the robotic system, an anatomic knee joint coordinate system was defined for each knee based on palpable and visual tibial and femoral anatomic landmarks. Three-dimensional coordinates representing the medial and lateral epicondyles, medial and lateral joint lines, and the tibial and femoral diaphyses[20,47] were collected using a portable measuring arm with a manufacturer-reported point repeatability of 0.025 mm (Romer Absolute Arm; Hexagon Metrology).

Before the robotically simulated clinical knee examination, the passive flexion-extension path was determined for each intact knee from full extension to 120° in 1° increments. Forces and torques in the remaining 5 DOFs were minimized (<5 N and <0.5 N·m, respectively), and knee positions were recorded to serve as reference starting points for subsequent testing. All sectioning and reconstruction procedures were performed with the knee positioned in neutral rotation determined by the recorded passive path. A 10-N compressive load was applied coincident to the tibial axis to ensure contact between the femoral condyles and tibial plateau during passive path and subsequent testing.

ACL Sectioning and Reconstruction

A single orthopaedic surgeon (G.M.) performed all ACLRs. An anatomic single-bundle (SB) ACLR using a bone–patellar tendon–bone (BTB) allograft (Allosource) was performed according to a previously reported technique.[18] Bone plugs were sized to 10 mm in diameter and 25 mm in length. The tibial and femoral footprints of the native ACL were visually identified through a medial parapatellar arthrotomy with the knee flexed to 120° of flexion. The ACL was

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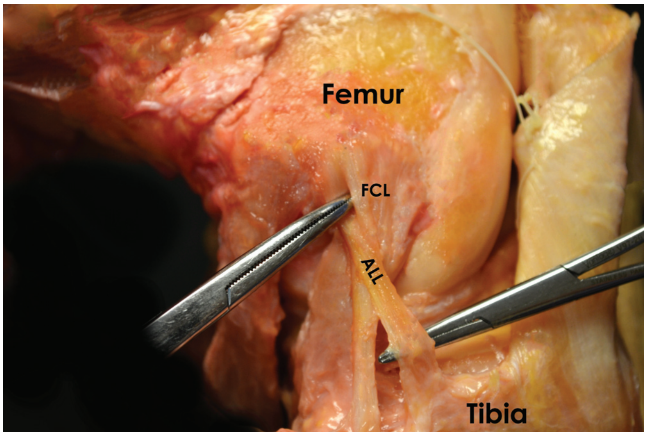

Figure 1. The course of the ALL in the right knee of a cadaveric specimen. The proximal attachment is located posterior and proximal to the FCL. The ALL crosses the FCL superficially and inserts distally into the tibia approximately midway between the center of the Gerdy tubercle and the anterior margin of the fibular head. ALL, anterolateral ligament, FCL, fibular collateral ligament.

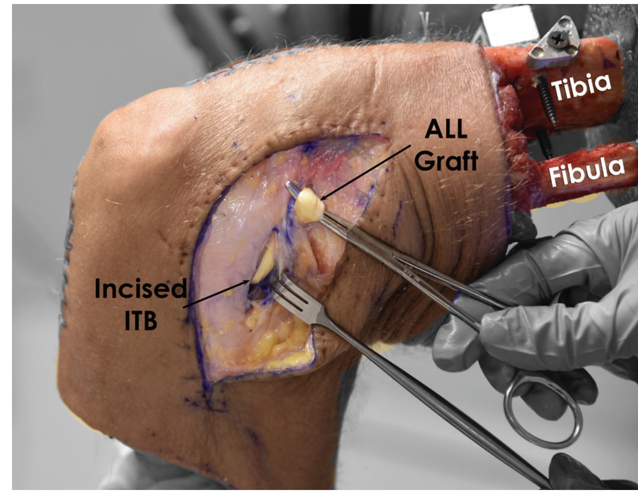

Figure 2. An inverted right knee mounted in the robotic system showing the anterolateral ligament (ALL) graft passed deep to the superficial layer of the ITB, superficial to the FCL, and through the transtibial tunnel on an inverted right knee. ITB, iliotibial band; FCL, fibular collateral ligament.

sectioned at both tibial and femoral attachments. An over-the-top guide (Arthrex Inc) was used to drill a guide pin for the ACL femoral tunnel through the center of the ACL footprint between the anteromedial and posterolateral bundles. A 10-mm low-profile reamer (Arthrex Inc) was used to ream a closed-socket femoral tunnel to a depth of 25 mm while maintaining a 1-mm back wall. Next, an ACL aiming device (Arthrex Inc) was positioned for ACL tibial tunnel placement, as described by LaPrade et al,[25] to avoid injury to the anterior lateral meniscus root, and a guide pin was drilled through the ACL footprint. A 10-mm acorn reamer was used in antegrade to ream a tibial tunnel. The femoral end of the BTB graft was fixed in the femur with a 7 × 20–mm cannulated titanium interference screw (Arthrex Inc). The other end was fixed in the tibial tunnel with the knee in full extension with a 9 × 20–mm cannulated titanium interference screw (Arthrex Inc) while applying a distal traction force of 88 N measured by a 500-N digital dynamometer (Quantrol; Weigh-Tronix Inc).

ALL Sectioning and Reconstruction

ALLRs were performed by a single orthopaedic surgeon (G.M.) in accordance with the technique described by Nitri et al[34] to replicate the native ALL anatomy (Figure 1). The knee was positioned at 75°, and a 1-cm transverse incision was made over the ALL tibial attachment site.[24] Soft tissue was carefully dissected down to bone to section the ALL from its tibial attachment. A guide pin was drilled in the center of the ALL tibial attachment site, midway between the center of the Gerdy tubercle and the anterior margin of the fibular head, and 9.5 mm distal to the joint line.[24] A 6-mm reamer (Arthrex Inc) was then used to ream a transtibial tunnel to facilitate passage of the ALL graft. A 2-cm horizontal incision into the biceps femoris bursa was next made to access the fibular collateral ligament (FCL)[27] and a midsubstance traction suture was placed to help locate the proximal FCL attachment. Next, a 3-cm incision was made through the superficial layer of the ITB directly over the lateral epicondyle, and tension was applied on the FCL tag stitch to identify the FCL femoral attachment. The ALL femoral attachment was identified 4.7 mm proximal and posterior to the FCL attachment site as described by Kennedy et al.[24] A guide pin was drilled into the ALL femoral attachment, aiming anteriorly and proximally to avoid the trochlea and collision with the ACLR tunnel. A 6-mm reamer (Arthrex Inc) was used to ream a closed-socket ALL femoral tunnel to a depth of 30 mm.

Commercially prepared semitendinosus allografts (Allosource) were trimmed to 12 cm in length, and both ends of each graft were tubularized to a diameter of 6 mm using No. 2 polyethylene/polyester sutures (FiberLoop; Arthrex Inc). The ALL graft was fixed in the femur with a 7 × 23–mm biointerference screw (Arthrex Inc) with traction applied to ensure sturdy fixation. The graft was then passed deep (medial) to the superficial layer of the ITB, superficial (lateral) to the FCL, and through the transtibial tunnel (Figure 2).

The protruding whipstitches from the ALL graft were fastened through a custom fixation clamp while applying 88 N of traction force. The clamp was mounted on the anteromedial aspect of the tibia >6 cm distal from the joint line to avoid interfering with the superficial medial collateral ligament attachment. During pilot testing, the custom fixation clamp was validated against slippage, and load to failure was evaluated using a dynamic tensile testing machine (ElectroPuls E10000; Instron). The suture-fixation device exhibited negligible slippage and failed at >250 N, which exceeded our testing forces.

Biomechanical Testing

Biomechanical testing was performed according to previously described robotically simulated clinical examinations.[14,18] Full kinematic assessment, including pivot-shift, anterior drawer, and internal rotation tests, was performed for each of the following states: (1) intact; (2) SB ACLR with intact ALL; (3) SB ACLR with sectioned ALL; (4) SB ACLR with ALLR using graft fixation angles of 0° (ALLR0), 15° (ALLR15), 30° (ALLR30), 45° (ALLR45), 60° (ALLR60), 75° (ALLR75), and 90° (ALLR90); and (5) sectioned ACL and ALL. A pivot-shift test for anterolateral rotatory instability was simulated by a coupled 5-N·m internal rotation torque and a 10-N·m valgus torque and applied at 0°, 15°, 30°, 45°, and 60° of flexion. An 88-N anterior drawer test for tibial translation and a 5-N·m internal rotation torque test for rotational laxity were performed at 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120°. The simulated pivot-shift test included a 10-N compressive force to ensure tibiofemoral contact and may not precisely simulate the highly dynamic pivot-shift test performed in the clinical setting. Randomization of tested flexion and fixation angle order was performed for each specimen to distribute any potential effects of repetitive testing over the reconstructed states.

Data Collection

During all robotically simulated clinical examinations, displacement and rotation of the tibia were recorded in all directions at the center of the joint line. Rotations were expressed as intrinsic Euler angles, and the center of the joint line was determined by the points collected with the portable measuring arm. During the simulated pivot-shift test, knee joint motion was reported by both internal rotation (degrees) and axial plane translation (mm). Axial plane translation was determined by calculating the vector sum of the displacement of the most lateral aspect of the tibial plateau in the anterior and medial directions.[18,33] Data were reported for the internal rotation test as degrees of rotation about the tibial shaft. During the simulated anterior drawer test, data were reported as anterior translation (mm) of the tibia.

Statistical Analysis

Two-factor linear mixed-effects models were constructed to assess the effects of fixation angle and flexion angle on anterior displacement and internal rotation. Random intercepts were given to each specimen to account for the repeated-measures nature of the study design. A cubic polynomial was fit to the flexion angle variable, and an interaction effect was excluded from the model as suggested by the Bayesian information criterion. Residual diagnostics were performed to confirm model assumptions and model fit. To address the primary hypotheses of the study, Tukey post hoc comparisons were made between fixation angles when the main effect was significant.

In addition, to assess over- and underconstraint relative to intact and differences from the ACLR with the ALL cut state, paired t tests were computed for each fixation/flexion angle. No adjustments for multiple comparisons were made within this set of dependent statistical tests; thus, the type 1 error rate was controlled on a comparison-wise level only. Overconstraint was determined by the reduction of joint motion beyond the intact state and was deemed significant according to the paired t test results. The statistical software R was used for all analyses (R Foundation for Statistical Computing with lme4 and multcomp packages).[4,22,37] Data were reported for each testing condition as the mean (± SD) change in translation (mm) or rotation (degrees) compared with the intact state.

RESULTS

Internal Rotation During an Applied Internal Rotation Torque

When subjected to a 5-N·m internal rotation torque, the ACLR with the sectioned ALL state displayed significantly increased internal rotation compared with the intact state at flexion angles 15° through 75° (0.8°-1.2°; $P < .05$). Anterolateral ligament reconstruction, depending on fixation angle, produced significant overconstraint of internal rotation with respect to the intact state at flexion angles ≥30° (1°-3.7°; $P < .05$), except for ALLR0 at 30° of flexion. When compared with the ACLR with the sectioned ALL state, ALLR significantly reduced internal rotation at flexion angles beyond 15°, regardless of fixation angle ($P < .05$), except for ALLR75 at 15° of flexion. All data for internal rotation observed during a 5-N·m internal rotation torque are reported in Table 1. Mean internal rotation and corresponding significance for all ACL and ALL reconstructed states with respect to the intact state are shown in Figure 3.

The 2-factor model found a nonsignificant ALLR fixation angle effect ($P = .095$), indicating that internal rotation did not significantly differ among graft fixation angles, regardless of tested flexion angle.

Internal Rotation During a Simulated Pivot-Shift Test

Under the application of a combined 5-N·m internal rotation torque and a 10-N·m valgus torque, the ACLR with sectioned ALL state exhibited significantly increased internal rotation compared with the intact state at flexion angles 15° through 60° (1.1°-1.5°; $P < .05$). ALLR, depending on fixation angle, demonstrated significant overconstraint relative to the intact state at flexion angles 45° and 60° (1.7°-2.9°; $P < .05$). When compared with the ACLR with the sectioned ALL state, ALLR significantly reduced internal rotation at flexion angles beyond 30°, regardless of fixation angle ($P < .05$). All data representing internal rotation during the pivot-shift test are reported in Table 2. Mean internal rotation and corresponding significance for all ACL and ALL reconstructed states with respect to the intact state are shown in Figure 4.

The 2-factor model found a nonsignificant effect of different fixation angles for ALLR ($P = .593$), indicating that internal rotation during a simulated pivot-shift test

TABLE 1
Resultant Mean Internal Rotation (in degrees) for All Knees Subjected to a 5-N·m Internal Rotation Torque[a]

	Flexion Angle								
State	0°	15°	30°	45°	60°	75°	90°	105°	120°
Intact	9.3 ± 2.1	14.0 ± 2.9	18.0 ± 3.8	19.0 ± 4.4	18.2 ± 5.0	16.0 ± 4.2	14.9 ± 3.5	14.6 ± 3.4	14.5 ± 3.7
ACLR + ALL intact	9.8 ± 2.7	14.5 ± 3.2	18.3 ± 4.0	19.3 ± 4.6	18.5 ± 4.9	16.3 ± 4.3	14.9 ± 3.4	14.8 ± 3.5	14.5 ± 4.0
ACLR + ALL cut	10.0 ± 2.9	14.8 ± 3.3	19.0 ± 4.2	19.8 ± 4.9	19.2 ± 5.4	17.2 ± 5.1	15.6 ± 4.3	15.1 ± 3.9	15.1 ± 4.1
ACL + ALL cut	11.9 ± 3.1	16.3 ± 3.7	19.3 ± 4.7	19.8 ± 5.2	19.2 ± 5.4	17.2 ± 5.2	15.9 ± 4.6	15.4 ± 4.4	15.2 ± 4.3
ALLR (fixation angle) + ACLR									
0°	9.4 ± 3.1	13.3 ± 3.6	16.7 ± 4.8	16.9 ± 5.3	16.5 ± 5.2	14.6 ± 4.6	13.0 ± 4.2	12.4 ± 4.2	11.7 ± 4.1
15°	9.5 ± 3.0	13.9 ± 3.4	16.6 ± 4.6	17.0 ± 4.7	16.0 ± 4.6	14.4 ± 4.1	13.3 ± 3.3	11.5 ± 4.0	11.6 ± 4.2
30°	9.5 ± 2.9	14.1 ± 3.5	17.0 ± 4.6	16.9 ± 4.7	16.3 ± 4.7	13.9 ± 3.9	12.4 ± 4.3	12.3 ± 4.3	11.8 ± 4.4
45°	9.3 ± 3.1	14.0 ± 3.2	16.7 ± 4.1	16.9 ± 4.5	16.3 ± 4.9	14.4 ± 4.1	11.7 ± 3.3	11.6 ± 3.4	11.6 ± 3.5
60°	9.5 ± 3.4	13.6 ± 3.8	16.3 ± 4.6	16.4 ± 4.5	15.4 ± 4.3	13.7 ± 3.5	11.6 ± 3.4	11.0 ± 3.7	10.8 ± 4.2
75°	9.3 ± 3.0	14.0 ± 3.8	16.3 ± 3.9	17.0 ± 4.6	15.9 ± 4.6	14.4 ± 4.2	13.2 ± 3.7	12.1 ± 3.9	11.9 ± 3.8
90°	8.9 ± 3.2	13.6 ± 3.9	16.5 ± 4.6	17.1 ± 4.9	16.3 ± 4.6	14.2 ± 4.2	12.1 ± 3.4	11.6 ± 3.8	11.7 ± 3.7

[a]Data are expressed as mean ± SD. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament; ALLR, anterolateral ligament reconstruction.

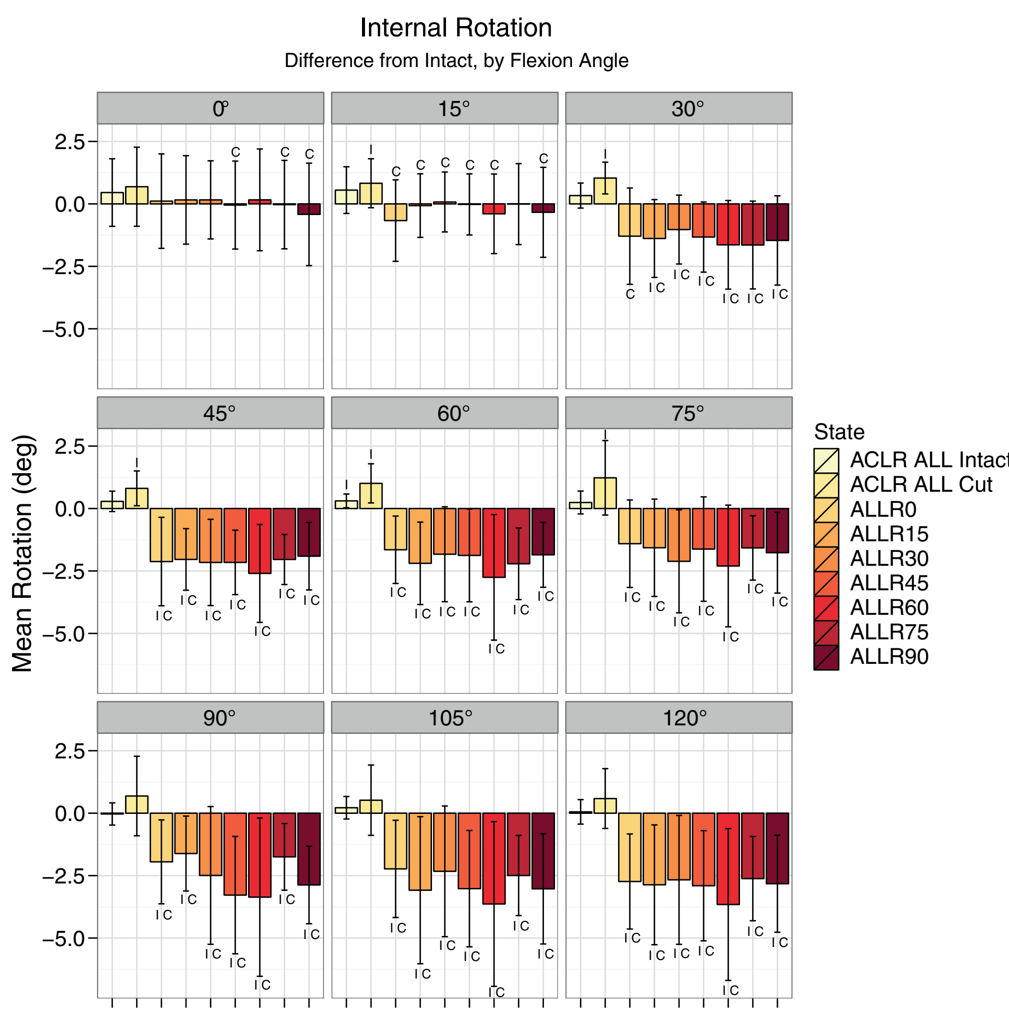

Figure 3. Mean changes in internal rotation (error bars represent 1 SD) in response to an applied 5-N·m internal rotation torque after ACLR + intact ALL, ACLR + ALL cut, and ACLR + ALLR with varying graft fixation angles. Significantly different (*P* < .05) [I]from intact state and [C]from ACLR with ALL cut state. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.

TABLE 2
Resultant Mean Internal Rotation (in degrees) for All Knees Subjected to a Simulated Pivot-Shift Test (5-N·m internal rotation torque + 10-N·m valgus torque)[a]

State	Flexion Angle 0°	15°	30°	45°	60°
Intact	9.4 ± 2.2	14.5 ± 2.9	18.8 ± 3.7	19.9 ± 4.4	19.1 ± 5.0
ACLR + ALL intact	9.9 ± 2.9	15.3 ± 3.3	19.5 ± 3.9	20.5 ± 4.6	19.6 ± 5.0
ACLR + ALL cut	10.1 ± 3.2	15.6 ± 3.3	20.3 ± 4.0	21.2 ± 4.8	20.6 ± 5.2
ACL + ALL cut	11.9 ± 3.2	16.7 ± 3.5	20.2 ± 4.1	20.8 ± 4.8	20.2 ± 4.7
ALLR (fixation angle) + ACLR					
0°	9.6 ± 3.5	14.0 ± 3.9	17.7 ± 4.9	17.7 ± 5.4	17.4 ± 5.0
15°	9.7 ± 3.3	14.8 ± 3.6	17.6 ± 4.6	17.7 ± 4.7	16.7 ± 4.4
30°	9.7 ± 3.1	14.9 ± 3.7	18.0 ± 4.7	17.6 ± 4.8	17.1 ± 4.4
45°	9.5 ± 3.5	14.8 ± 3.4	17.7 ± 4.0	17.7 ± 4.3	17.1 ± 4.5
60°	9.6 ± 3.6	14.3 ± 4.1	17.3 ± 4.8	17.1 ± 4.7	16.2 ± 4.3
75°	9.5 ± 3.2	14.8 ± 3.9	17.3 ± 4.0	17.8 ± 4.6	16.7 ± 4.5
90°	9.1 ± 3.5	14.5 ± 4.1	17.5 ± 4.6	17.9 ± 4.9	17.1 ± 4.4

[a]Data are expressed as mean ± SD. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament; ALLR, anterolateral ligament reconstruction.

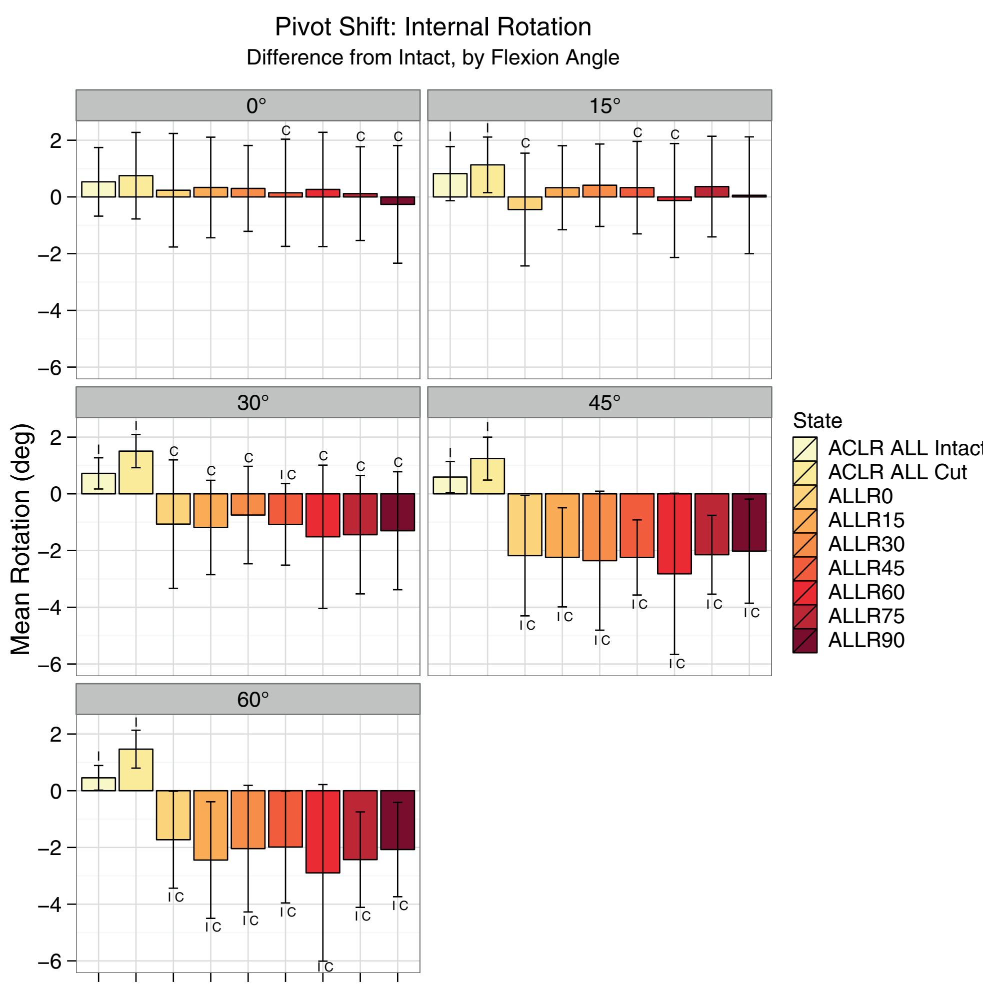

Figure 4. Mean changes in internal rotation (error bars represent 1 SD) in response to an applied combination of a 5-N·m internal rotation torque and a 10-N·m valgus torque after ACLR + intact ALL, ACLR + ALL cut, and ACLR + ALLR with varying graft fixation angles. Significantly different ($P < .05$) [I]from intact state and [C]from ACLR with ALL cut state. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.

did not significantly differ among ALL graft fixation angles, regardless of tested flexion angle.

Axial Plane Translation During a Simulated Pivot-Shift Test

When subjected to a combined 5-N·m internal rotation torque and 10-N·m valgus torque, the ACLR with the sectioned ALL state exhibited significantly increased axial plane translation compared with the intact state (1.1-1.6 mm; $P < .05$) beyond 30° of knee flexion. ALLR15, ALLR45, and ALLR75 demonstrated significant overconstraint of axial plane translation relative to the intact state at 45° and 60° of knee flexion (1.0-1.5 mm; $P < .05$), except for ALLR45 at 60° of flexion. When compared with the ACLR with ALL cut state, ALLR significantly reduced axial plane translation beyond the intact state at flexion angles 30°, 45°, and 60° (0.4-2.1 mm; $P < .05$). All data for axial plane translation observed during the pivot-shift test are reported in Table 3. Mean axial plane translation and corresponding significance for all ACL and ALL reconstruction states with respect to the intact state are shown in Figure 5.

The 2-factor model found a nonsignificant ALLR fixation angle effect ($P = .189$), indicating that axial plane displacement during a simulated pivot-shift test did not significantly differ among ALL graft fixation angles, regardless of the knee flexion angle.

Anterior Tibial Translation During an Anterior Tibial Load

During an applied 88-N anterior tibial load, the ACLR with the sectioned ALL state exhibited significantly increased anterior tibial translation compared with the intact state at flexion angles 0° through 75° (0.5-1 mm; $P < .05$), except for 45° ($P > .05$). Similar significant increases relative to intact were found for the ACLR with the intact ALL state at flexion angles 0°, 15°, 30°, and 60° (0.5-0.9 mm; $P < .05$). Compared with the intact state, ALLR at all tested fixation angles displayed similar anterior translation to that of the ACLR with sectioned ALL state (0.4-1.3 mm; $P < .05$), except for ALLR45 at 0° and 45° of flexion; ALLR60 at 105° of flexion; ALLR75 at 0°, 30°, and 45° of flexion; and ALLR90 at 0° of flexion. All data for anterior tibial translation observed during an 88-N anterior drawer are reported in Table 4. Mean anterior displacement and corresponding significance for all ACL and ALL reconstructed states with respect to the intact state are demonstrated in Figure 6.

The 2-factor model found a nonsignificant ALLR fixation angle effect ($P = .576$), indicating that anterior translation did not significantly differ among ALL graft fixation angles, regardless of the knee flexion angle.

DISCUSSION

The most important finding of this study was that an anatomic ALLR in the setting of a concomitant ACLR resulted in significant rotational overconstraint of the knee joint for most flexion angles and for all ALLR graft fixation angles. Although ALLR at nearly all fixation angles resulted in significant reduction of rotational laxity compared to the ACLR with a deficient ALL state, no anatomic-based ALLR was capable of restoring stability without overconstraint of normal joint kinematics. Furthermore, no ALL graft fixation angle was significantly different from any other during an anterior drawer test, pivot-shift test, or internal rotation test.

The results of this study demonstrate similar findings to previous biomechanical studies that evaluated lateral extra-articular tenodesis (LET) procedures.[10,13,31,39] Historically, LET procedures were performed to restore anterolateral rotatory stability when a patient had an ACL injury.[6,7,11] From a biomechanical perspective, LET procedures have failed to restore native joint kinematics, demonstrating internal tibial rotation overconstraint.[5,9,10,13,31,39] These procedures have been reported to potentially interfere with normal knee joint motion[39] by causing the tibia to be positioned in an externally rotated position.[13]

Earlier clinical studies reported high failure rates and poor long-term functional outcomes after LET procedures.[37,45,48] Zaffagnini et al[49] reported lower subjective, objective, and functional results for an SB ACLR augmented with an ITB tenodesis compared with an anatomic double-bundle ACLR. O'Brien et al[35] reported that 40% of 48 reviewed patients treated with combined ACL and extra-articular lateral-sling reconstructions had long-term chronic pain and/or swelling at an average 4-year follow-up. Similarly, Sgaglione et al[42] reported on 70 patients and found that 15.7% of patients repaired with a lateral sling in addition to an ACLR had chronic lateral knee pain at a mean 3-year follow-up. Several authors have also reported no significant benefits of adding an LET to an intra-articular ACLR.[1,3,16,17,35,38,42] Marcacci et al[30] reported highly satisfactory results for 54 patients treated with a combined ACLR and LET at a mean 11-year follow-up and observed no increased incidence of osteoarthritis. However, this prospective study lacked a control group for comparison.

Hewison et al[21] performed a thorough systematic review on the outcomes of ACLR with and without LET procedures and concluded that LET augmentation of ACLR is an effective treatment for reducing rotatory laxity and eliminating the pivot shift compared with ACLR alone. They reported no significant differences in International Knee Documentation Committee (IKDC) or KT-1000/2000 measurements. In addition, they found no significant incidence of developing osteoarthritis or overconstraint between groups. However, they attributed the insignificance of these complications to the possibility of reporting bias and variability in follow-up length.

Biomechanical and clinical literature regarding the complications and difficulties of LET procedures contributed to the decreased popularity of these procedures for ACL injuries over the past 2 decades.[35,38,42,45,49] In recent years, there has been more focus on anatomic reconstruction of knee ligaments, and improved outcomes have been reported.[26,28,32] Earlier LET procedures were nonanatomic, and this could potentially explain some of the poor outcomes reported in the literature. Research on the ALL has resulted in a more detailed understanding of its anatomy, biomechanical properties, and influence on knee joint kinematics. Sonnery-Cottet et al[43] recently reported improved Lysholm

TABLE 3
Resultant Mean Axial Plane Translation (in mm) for Knees Subjected to a Simulated Pivot-Shift Test (5-N·m internal rotation torque + 10-N·m valgus torque)[a]

State	Flexion Angle, deg				
	0°	15°	30°	45°	60°
Intact	7.4 ± 2.0	11.4 ± 3.8	14.9 ± 5.3	15.9 ± 5.8	15.5 ± 5.4
ACLR + ALL intact	7.6 ± 2.3	11.8 ± 4.4	15.4 ± 5.8	16.4 ± 6.3	16.2 ± 5.7
ACLR + ALL cut	7.8 ± 2.6	12.2 ± 4.4	16.1 ± 6.1	17.0 ± 6.4	17.1 ± 5.9
ACL + ALL cut	9.8 ± 4.3	13.7 ± 7.4	16.9 ± 8.5	17.9 ± 8.4	17.8 ± 6.9
ALLR (fixation angle) + ACLR					
0°	7.5 ± 2.6	11.1 ± 4.2	14.3 ± 6.6	14.7 ± 7.2	14.8 ± 6.4
15°	7.6 ± 2.6	11.7 ± 4.5	14.3 ± 6.4	14.5 ± 5.9	14.0 ± 5.1
30°	7.6 ± 2.4	11.8 ± 4.5	14.5 ± 6.0	14.4 ± 5.5	14.4 ± 5.1
45°	7.5 ± 2.7	11.8 ± 4.3	14.4 ± 5.9	14.8 ± 5.9	14.8 ± 5.6
60°	7.5 ± 2.7	11.3 ± 4.4	13.7 ± 5.3	13.8 ± 5.1	13.4 ± 4.5
75°	7.5 ± 2.5	11.8 ± 4.7	13.9 ± 5.8	14.6 ± 6.0	14.1 ± 5.7
90°	7.2 ± 2.6	11.5 ± 4.7	14.1 ± 6.2	14.8 ± 6.1	14.6 ± 5.5

[a]Data are expressed as mean ± SD. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament; ALLR, anterolateral ligament reconstruction.

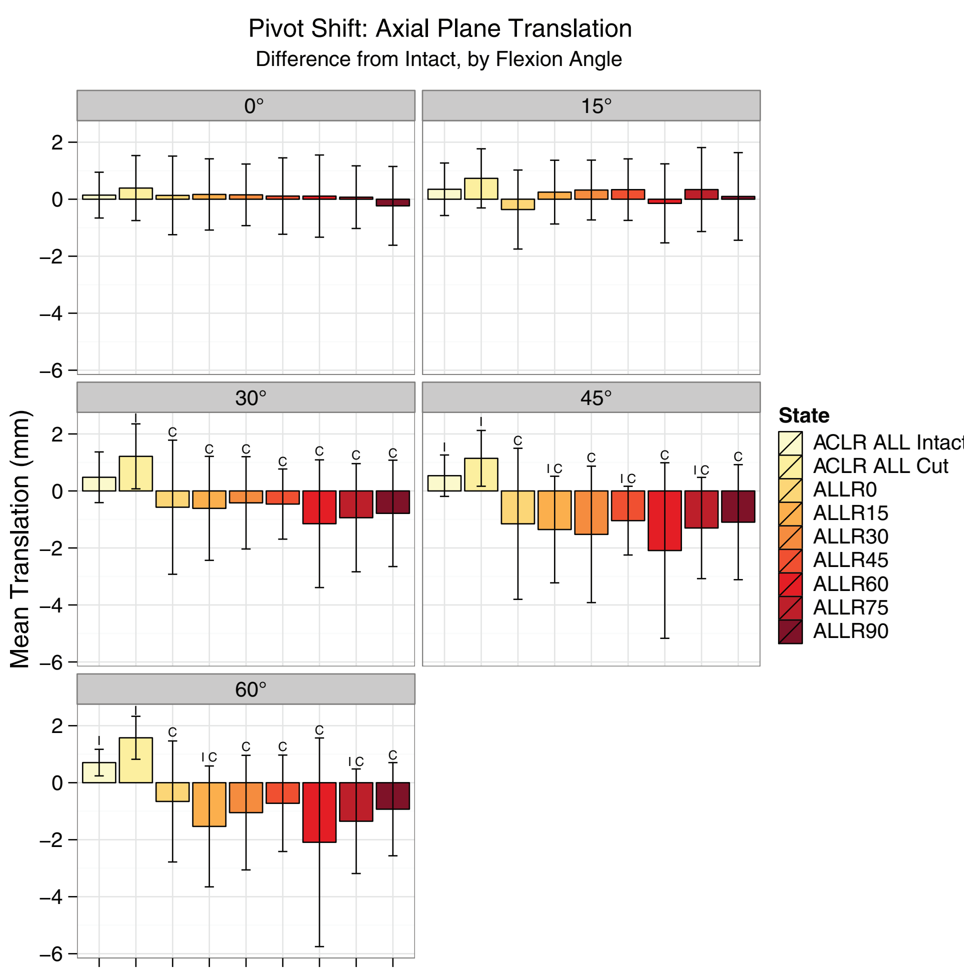

Figure 5. Mean changes in axial plane translation (error bars represent 1 SD) in response to an applied combination of a 5 N·m internal rotation torque and a 10 N·m valgus torque after ACLR + intact ALL, ACLR + ALL cut, and ACLR + ALLR states with varying graft fixation angles. Significantly different ($P < .05$) [I]from intact state and [C]from ACLR with ALL cut state. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.

TABLE 4
Resultant Mean Anterior Translation (in mm) for Knees Subjected to an 88-N Anterior Drawer Force[a]

	Flexion Angle, deg								
State	0°	15°	30°	45°	60°	75°	90°	105°	120°
Intact	3.3 ± 0.5	3.8 ± 0.6	4.3 ± 1.0	4.6 ± 1.2	4.0 ± 1.1	3.3 ± 1.0	2.9 ± 0.9	2.8 ± 0.8	2.7 ± 0.6
ACLR + ALL intact	3.9 ± 0.4	4.5 ± 0.4	4.7 ± 0.8	5.1 ± 0.9	4.8 ± 1.1	3.9 ± 1.0	3.5 ± 1.1	3.7 ± 1.4	3.5 ± 1.6
ACLR + ALL cut	3.9 ± 0.3	4.5 ± 0.5	4.8 ± 1.1	5.0 ± 1.0	4.8 ± 1.0	4.2 ± 1.3	3.7 ± 1.3	3.6 ± 1.5	3.6 ± 1.8
ACL + ALL cut	7.3 ± 1.4	10.8 ± 2.3	12.4 ± 3.4	12.1 ± 3.8	9.9 ± 3.5	7.8 ± 2.9	6.7 ± 2.3	6.2 ± 1.9	6.0 ± 1.7
ALLR (fixation angle) + ACLR									
0°	3.8 ± 0.4	4.6 ± 0.6	5.2 ± 1.1	5.9 ± 1.3	5.2 ± 1.3	4.5 ± 1.4	4.0 ± 1.4	3.8 ± 1.4	3.8 ± 1.6
15°	3.8 ± 0.4	4.6 ± 0.5	5.2 ± 1.0	5.5 ± 1.1	5.1 ± 1.2	4.5 ± 1.2	3.9 ± 1.3	3.9 ± 1.5	3.8 ± 1.6
30°	3.7 ± 0.4	4.6 ± 0.5	5.2 ± 1.0	5.5 ± 1.1	5.1 ± 1.2	4.4 ± 1.2	3.9 ± 1.3	3.7 ± 1.4	3.8 ± 1.6
45°	3.7 ± 0.4	4.5 ± 0.5	5.1 ± 1.0	5.5 ± 1.3	5.1 ± 1.2	4.4 ± 1.3	3.8 ± 1.2	3.7 ± 1.3	3.7 ± 1.5
60°	3.8 ± 0.4	4.6 ± 0.5	5.1 ± 1.0	5.6 ± 1.2	5.1 ± 1.2	4.3 ± 1.2	3.8 ± 1.2	3.6 ± 1.4	3.7 ± 1.5
75°	3.8 ± 0.5	4.6 ± 0.6	5.3 ± 1.2	5.5 ± 1.2	5.3 ± 1.2	4.5 ± 1.4	3.9 ± 1.4	3.7 ± 1.4	3.7 ± 1.5
90°	3.7 ± 0.5	4.6 ± 0.4	5.2 ± 0.9	5.5 ± 1.0	5.0 ± 1.2	4.4 ± 1.3	3.9 ± 1.3	3.8 ± 1.3	3.7 ± 1.6

[a]Data are expressed as mean ± SD. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament; ALLR, anterolateral ligament reconstruction.

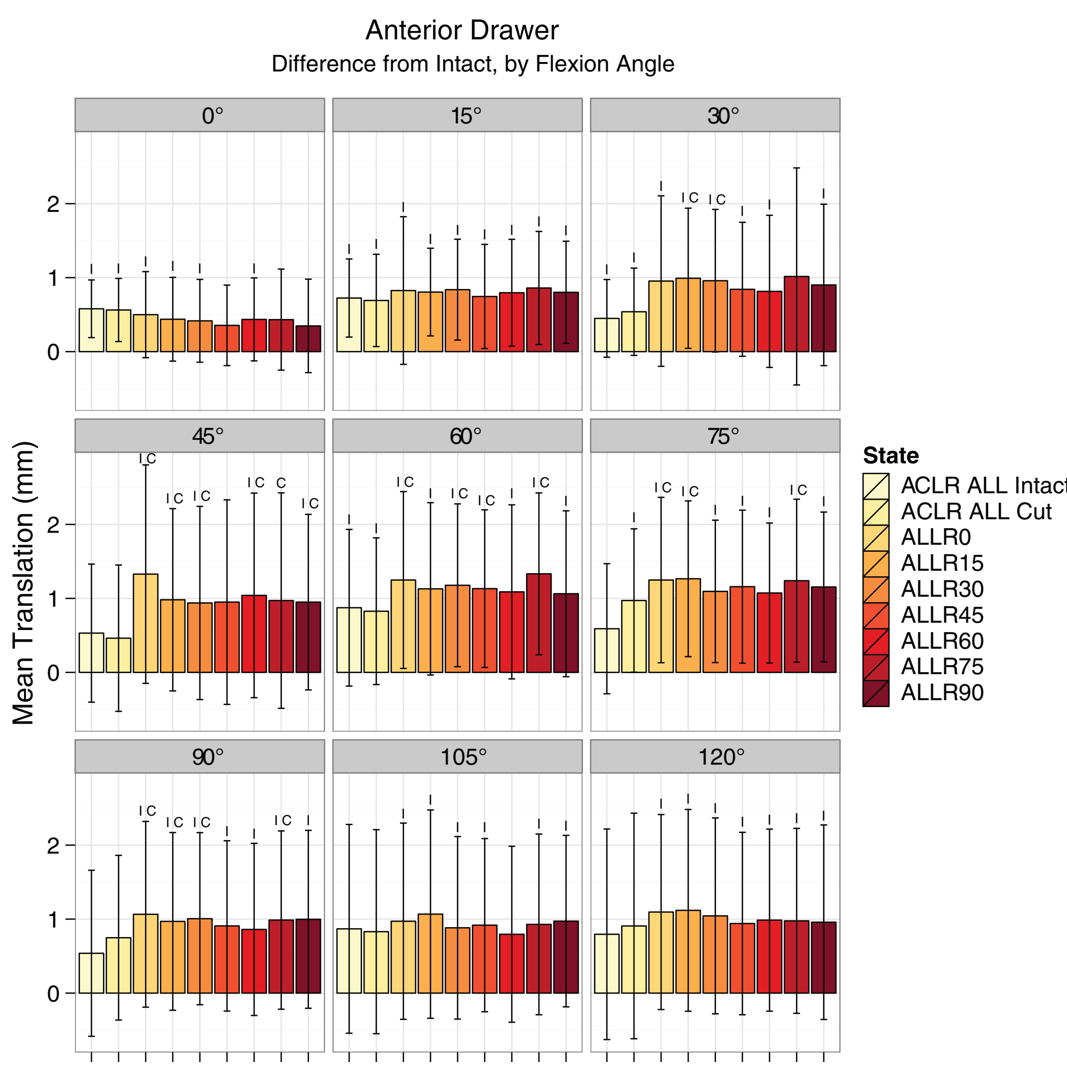

Figure 6. Mean changes in anterior translation (error bars represent 1 SD) in response to an applied 88-N anterior drawer after ACLR + intact ALL, ACLR + ALL cut, and ACLR + ALLR with varying graft fixation angles. Significantly different ($P < .05$) [I]from intact state and [C]from ACLR with ALL cut state. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.

and IKDC subjective outcome scores at a minimum 2-year follow-up for combined ACLR and ALLR cases. All 83 patients in the study had a preoperative positive pivot-shift test result, and 91.6% had a negative pivot-shift test result postoperatively.[43]

The results of this study suggest that none of the currently recommended anatomic ALL graft fixation angles reported in the literature were capable of restoring anterolateral stability without introducing significant overconstraint of the knee. The amount of rotational overconstraint capable of affecting clinical outcomes is still a subject of debate. However, the presented data elicit concern that the overconstraint from a combined ACLR and ALLR may potentially lead to long-term discomfort, as abnormal joint restraint has been reported to increase the incidence of developing osteoarthritis,[38,40,45] stiffness,[23] and decreased physiological motion.[2,12,13,38,45] Therefore, use of an ALLR concurrent with an ACLR must be carefully evaluated, and the target patient population needs to be defined with further investigation.

We acknowledge some limitations of this study. Inherent to a time-zero cadaveric study, the results of this study do not reflect the graft biological incorporation effects on reconstruction performance or the possibility of graft stretching. In addition, the application of multiple loading conditions at each flexion angle may increase laxity of the surrounding soft tissue structures. However, this effect was limited by randomizing the order of graft fixation angles and tested flexion angles. We recognize that the external clamp used to fix the ALL graft at multiple fixation angles for each specimen was not consistent with clinical practice. Despite this, the tunnels for graft passage were still positioned in their anatomic locations, and the external clamp prevented introducing potential variables of tunnel widening and implant slippage. Furthermore, we limited the effect of dependent variables by using the same materials and commercially prepared allografts for every reconstruction. Consistency was maintained between manufacturer and reamer type during the surgical protocol to minimize aperture variability and tunnel dimensions.[15] Moreover, a single experienced surgeon (G.M.) performed all surgeries, and several pilot tests were completed to establish reproducible and highly accurate testing procedures using a 6 DOF robotic system. The robotic arm was static during all reconstruction procedures, including tensioning, which is not consistent with clinical practice; nevertheless, the clinical goal (albeit unattainable) is to constrain the various knee angles and other DOFs during graft tensioning. Therefore, the current setup mimicked the ideal clinical scenario without compromising the accuracy and repeatability of the results.[19] Finally, ALLR was performed with a 6-mm semitendinosus allograft and was tensioned to 88 N during fixation. We recognize that graft choice, size, and tension are potential variables and were not investigated in the present study.

CONCLUSION

The results of this study suggest that an anatomic ALLR in conjunction with an ACLR resulted in joint overconstraint. Furthermore, none of the clinical recommendations found in the current literature for ALLR graft fixation angles restored normal joint kinematics in this study. This study raised concerns on the ability of combined ACL and ALL reconstructions to safely restore native joint kinematics without causing joint overconstraint. Further investigations into the application, target population, and distinct surgical techniques for ALLR are strongly recommended.

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